Imagers Provide Eyes to

Gamma-ray imagers with improved detection capabilities help security agencies search for illicit radioactive sources.

THE ability to detect gamma rays is a vital tool for many areas of research. Gamma-ray detectors allow scientists to study celestial phenomena and diagnose medical diseases, and they have been used to determine the yield in an underground nuclear test. Today, these detectors are an important tool for homeland security, helping the nation confront new security challenges. Government agencies need detectors for the scenarios in which a terrorist might use radioactive materials to fashion a destructive device targeted

See Gamma Rays

against civilians, structures, or national events. To better detect and prevent terrorist attacks, the Department of Homeland Security (DHS) is funding projects to develop a suite of detection systems that can search for illicit radioactive sources in different environments.

Livermore researchers have been applying their expertise in radiation detection for more than 30 years. For example, detectors designed for use in treaty inspections can monitor the location of nuclear missile warheads in a nonintrusive manner. (See *S&TR*, October 1995, pp. 14–26.) These detectors measure the gamma rays emitted from the isotopes of nuclear elements contained in weapons. Over the years, Laboratory researchers have developed a range of radiation detection instruments, including detectors on buoys for customs agents at U.S. maritime ports (see *S&TR*, January 2004, pp. 19–22), cargo interrogation systems (see *S&TR*, May 2004, pp. 12–15), and high-resolution handheld instruments that

emergency response personnel could use to search for a clandestine nuclear device (see *S&TR*, September 2004, pp. 4–11).

Gamma rays have the highest energy in the electromagnetic spectrum. They tend to go straight through matter, rather than reflect or bend as visible light does. Mirrors or lenses cannot be used to depict, or image, gamma rays, but their energy can measured indirectly by observing how photons interact with a detector material. For many applications, however, researchers need to accurately determine

where gamma rays originate, and doing so requires imaging technology.

For example, many radiation detectors have excellent energy resolution and sensitivity to sources within a range of several meters. At greater distances, however, the source can be lost in a clutter of background gamma-ray emission from the environment, including concrete, natural mineral deposits, and some foods.

Detector developers want to design instruments that quickly survey large areas at a distance and accurately distinguish illicit from background signals. However, when a detector covers a large area, the signal from an object in the background can mimic the signature from a source of interest, even though the sources are widely separated. For example, a concrete building 20 meters from the detector may register the same as an illicit source located farther away. This similarity makes the detection of weak signals impossible unless the characteristics of the background are known in advance—unlikely in searches for clandestine radioactive materials.

Two current projects at Lawrence Livermore are focused on creating gamma-ray images without mirrors or lenses. A multi-institutional collaboration led by Laboratory researchers has developed a large-area gamma-ray imager that significantly increases detection capabilities. Another Livermore team is designing a portable system that relies on Compton scattering to locate gamma-ray sources.

Accurate and Quick Detection

The technology to image gamma rays was introduced in 1957 by Hal Anger, an electrical engineer who worked at Lawrence Berkeley National Laboratory. The camera he developed uses gamma radiation to image metabolic processes within humans, allowing researchers to observe, for example, how blood flows and kidneys function. Biomedical and nuclear medicine research has resulted in improved technologies for gamma-ray imaging. Livermore scientists have partnered in several of these research efforts, such as the small animal radionuclide imaging system. (See *S&TR*, November 2004, pp. 4–11.) Advancements in nuclear medicine are thus contributing to the development
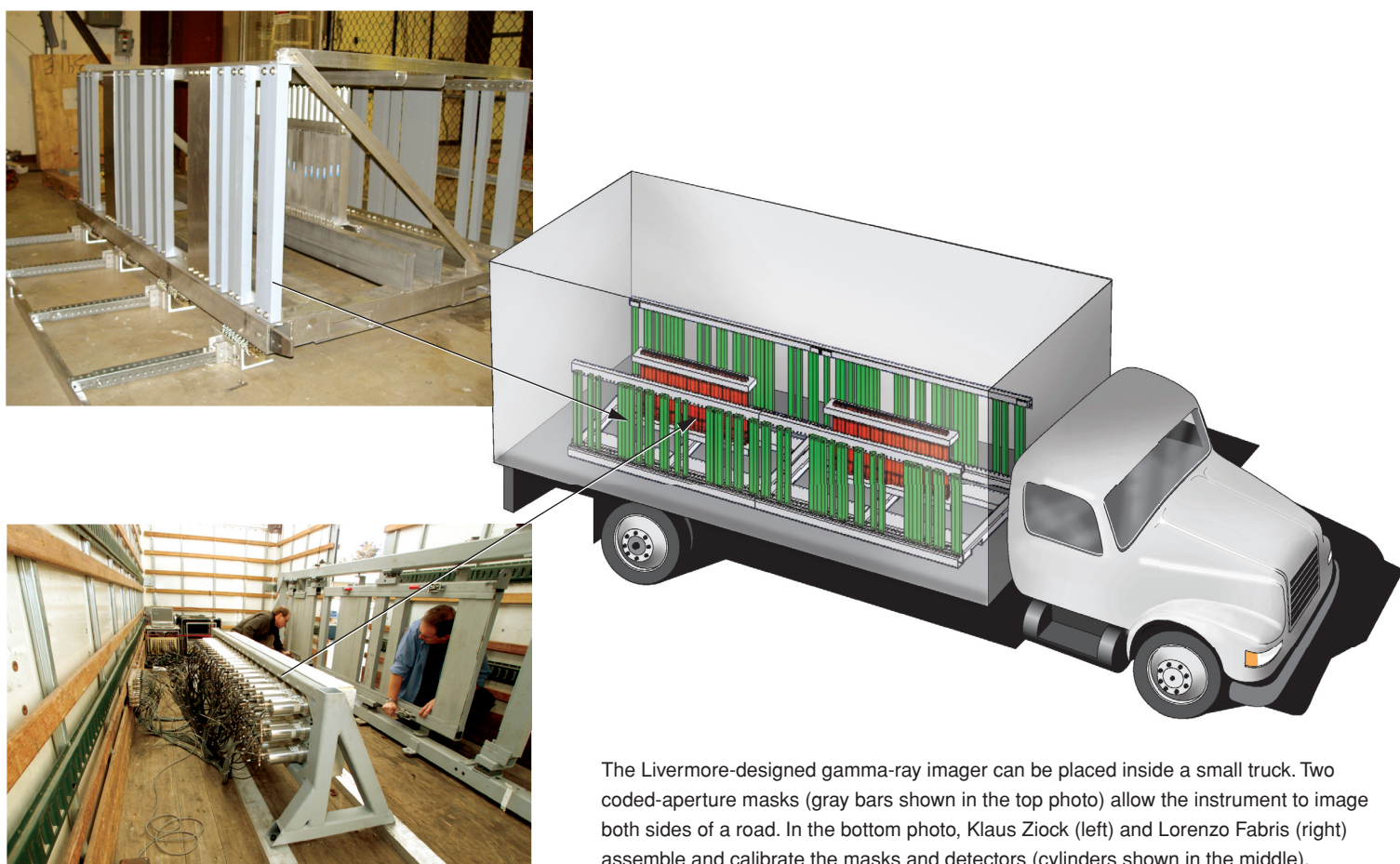
The Livermore-designed gamma-ray imager can be placed inside a small truck. Two coded-aperture masks (gray bars shown in the top photo) allow the instrument to image both sides of a road. In the bottom photo, Klaus Ziock (left) and Lorenzo Fabris (right) assemble and calibrate the masks and detectors (cylinders shown in the middle).

of gamma-ray imaging systems for homeland security.

In 2003, Livermore's Laboratory Directed Research and Development (LDRD) Program funded a project to demonstrate that imaging techniques could enhance the search capabilities over a large area. Led by Laboratory engineer Lorenzo Fabris, the project team included researchers from Pacific Northwest and Oak Ridge national laboratories, the Massachusetts Institute of Technology, and the University of California's (UC's) Space Sciences Laboratory at Berkeley. The collaboration demonstrated a large-area gamma-ray imager that can detect millicurie quantities of a cesium isotope located 85 meters away, even while the imager is traveling at 16 kilometers per hour.

With funding from DHS, the team developed the next-generation prototype imager in 2005. The instrument, which is approximately the size of a sofa, can detect gamma-ray energies ranging from 50 to 3,000 kiloelectronvolts—the energy range of interest in most national security applications—and its sensitivity is much greater than that of nonimaging instruments. Fabris says, "Because we are making an imager that can capture and distinguish many signals within a large area, we can design the radiation detector to be larger." The prototype instrument, which costs about $400,000, can be mounted on a small truck and used to surveil large areas quickly.

Masks Reveal True Signals

In designing this imager, the team adapted an imaging method originally developed for high-energy astrophysics. With this method, a coded aperture—a lead mask with holes drilled in a special pattern—is placed in front of a detector array. As the detector picks up gamma-ray signals, the photon energy passing through the mask casts shadows on the detector elements, which the imager records. The detector elements also measure the signal count and position. As the instrument travels through an area, it accumulates several shadow patterns, or "shadowgrams," and creates a pixel map of the radiation field of the surveyed region.

"Each pixel represents an area in the field of view," says Fabris. "The pixels are small enough that, when combined, they generate a detailed image of a source of interest. With one map of pixels, we can cover distances out to 100 meters."

The image generated from a coded-aperture process is derived from the variation in gamma-ray signal counts versus signal position on a detector. In an ideal situation, only the shadow cast by the mask would cause these variations. However, one shortfall of coded-aperture imagers is that gamma-ray sources outside an instrument's field of view can contribute to the signal count. This incident radiation may create shadows that cause the image to blur.

To compensate for the incident radiation, the team designed an antimask whose hole pattern is the inverse of the

Mask   Antimask   Gamma-ray source
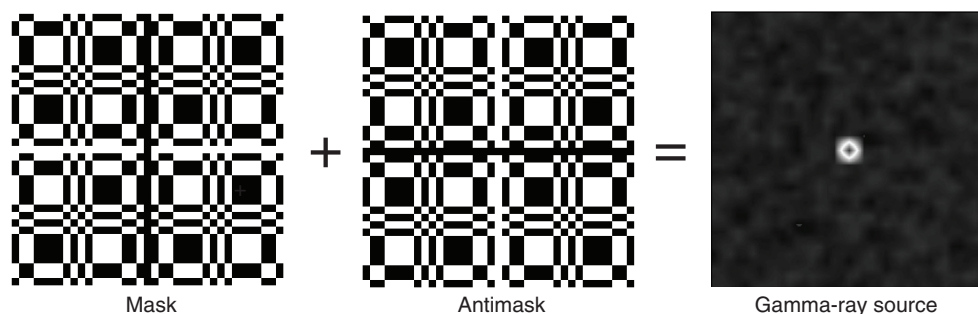
Combining a mask with an antimask whose hole pattern is the inverse of the mask's pattern effectively removes background signals outside the surveyed area.

(a)   (b)
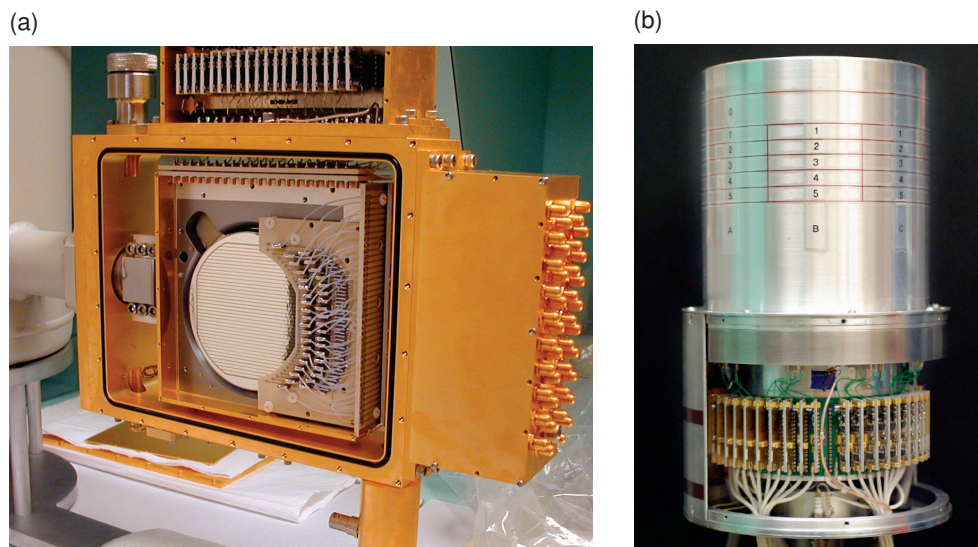
(a) In the disk configuration, the Compton imager has orthogonal strips on each side connected to a preamplifier and a digital data-acquisition system to determine the three-dimensional (3D) position for each gamma-ray interaction. (b) In the cylindrical configuration, the outside contact is divided into pixels that, when analyzed with a digital signal processor, provide the necessary 3D information.

pattern on the mask. Fabris explains, "The mask and the antimask are exposed to the source at the same time. Background signals outside the field of view would be extraneous signals. By subtracting the measurement taken with one mask from the inverse measurement taken with the antimask, we are left with only those signals that passed twice through the masks—once through the mask and once through the antimask." Each lead mask is 2 meters long and weighs 1,000 kilograms, comprising the bulk of the instrument's weight.

Pacific Northwest performed modeling studies to determine the best detector configuration. Fabris says, "The most practical material for the large-area gamma-ray detector is cesium iodide. It's less sensitive to potential damage induced by temperature changes than detector materials such as sodium iodide, and it is fairly inexpensive to produce in the large sizes necessary for this instrument." The cesium iodide is arranged in two arrays, one for the mask and one for the antimask. Researchers at the Space Sciences Laboratory and Oak Ridge provided navigational data and the image reconstruction and mapping algorithms. Physicist Klaus Ziock, who previously worked on the Livermore team and is now at Oak Ridge, contributed his expertise on coded-aperture systems.

The imager provides one-dimensional images simultaneously from both sides of a vehicle—a design choice based on its intended use in suburban or light-urban areas. The team is also considering a two-dimensional (2D) system that could image both gamma rays and visible light for use at choke points such as border crossings and tollbooths. "Ideally," says Fabris, "we want to integrate several small imagers that could track moving targets, for example, cars changing from one lane to another. In addition to serving homeland security, the technology could be used in imagers designed for medical research, by replacing the pinhole, or collimator, with coded-aperture masks.

Tracking Every Gamma Ray

Livermore's large-area gamma-ray detector has demonstrated that imaging can greatly improve detection sensitivity.

Recent advances in semiconductor detector manufacture and signal processing are allowing Livermore researchers to increase detection sensitivity further by designing gamma-ray imagers with omnidirectional capability. In another LDRD project, a Livermore team, led by physicist Kai Vetter, developed a gamma-ray imager that operates without a collimator or coded aperture. Instead, it relies on the principles of Compton scattering—the effect that occurs when a high-energy photon interacts with an electron in a material, resulting in a free electron and shifting the photon's energy and direction. If the gamma-ray photon still has enough energy after the interaction, the scattering process is repeated until the photon is stopped by the photoelectric effect, an atomic process that fully absorbs photons. (See the box below.)

Livermore's Compton imager can also merge images of gamma rays with visual images. In one experiment, the team combined a camera and a Compton imager to demonstrate that the system can visually identify a gamma-ray source containing an isotope of sodium.

The Principles behind Compton Scattering

The Compton imager is named after Arthur Holly Compton, who in 1923 observed that the wavelength of high-energy photons, such as x or gamma rays, increases when the photons interact with electrons in a material. This phenomenon is known as the Compton effect. According to quantum theory, a photon can transfer part of its energy to a loosely bound electron when the two collide. Because x- and gamma-ray photons have high energy, such collisions may transfer so much energy to an electron that it is ejected from its atom. The scattering of photons as they pass through and interact with a material is called Compton scattering. Compton won the Nobel Prize in physics in 1927 for his work on the scattering of high-energy photons by electrons.

Compton scattering is the principal absorption mechanism for gamma rays between 100 and 3,000 kiloelectronvolts. Uranium and plutonium both naturally emit radiation within this energy range. Below this range, photoelectric absorption is the dominant interaction type.

Compton imaging systems can be designed using various detector materials in different configurations. The key to optimizing imaging efficiency is to induce multiple interactions between the gamma ray and the detector material so the system can detect the full energy of the incident gamma ray. The gamma-ray interactions must be separated in space sufficiently so that they can be easily distinguished from each other and their positions can be accurately measured to obtain high angular resolution.

One requirement for Compton imaging is that a gamma ray must interact with electrons at least twice—once to induce Compton scattering and once to allow photoelectric absorption—although more than one scatter can occur. For example, a 1-megaelectronvolt gamma ray averages three Compton scattering interactions before it is finally photoelectrically absorbed by germanium. When an x- or gamma-ray photon is scattered or absorbed, high-energy electrons are ejected. The subsequent deposition of electron energy produces a large number of ionized atoms. The ionization from Compton scattering or photoelectric absorption is then recorded by the detectors.

Because the imager does not require gamma rays to enter the detector through a mask, it can identify radiation from all directions. Vetter says, "Compton scattering occurs whenever photons in the energy range of about 150 to 5,000 kiloelectronvolts are present. Our imager takes advantage of this effect. It calculates the angle of the incident gamma ray by measuring the positions and energies of the first two interactions with the detector."

Imaging systems based on Compton scattering were proposed 30 years ago for astrophysics and nuclear medicine applications. However, technology to improve sensitivity and reduce the system's size became available only in the past 10 years. Until recently, a Compton imager could not differentiate photon interactions in the scattering process because it could not determine the three-dimensional (3D) position of a gamma ray with sufficient fidelity. One technology breakthrough has been the 2D, segmented semiconductor detectors, which use materials such as germanium and silicon to improve energy resolution. The digital signal-processing equipment that is now available provides the necessary 3D position capability.

Designing the Optimal Imager

With funding from DHS, the Livermore team is developing a compact, portable Compton imager that will detect and identify sources between 120 to 3,000 kiloelectronvolts and provide unsurpassed sensitivity. The team has planned three generations of the instrument so design changes can be evaluated at each stage. Monte Carlo simulations showed that the highest sensitivity could be achieved by combining high-energy and position-resolution semiconductor detectors to maximize efficiency. Vetter explains, "For the imager to create an image based on data from the Compton effect, incoming gamma rays must interact with the detector at least twice—once to scatter the photon energy and again to absorb the photon. A semiconductor with a low atomic number, such as silicon, induces scattering very well, while one with a high atomic number, such as germanium, is effective at absorbing gamma rays."

Livermore's Compton imager uses four layers of detectors: two silicon crystals and two germanium crystals, together measuring about 8 by 8 by 6 cubic centimeters. The detectors are manufactured at Lawrence Berkeley National Laboratory and the Research Centre Jülich in Germany. With its 3D position capability and combined detector materials, the system can track gamma-ray interactions to a resolution of 0.5 millimeter.

A detection system based on tracking gamma rays provides unprecedented sensitivity not only for Compton imaging but also for nuclear spectroscopy, which is used to identify nuclear materials. "The Compton imager can distinguish gamma rays that deposit only partial energy in the detector from those that are fully absorbed," says Vetter, "so background signals can be more easily eliminated." The system applies the Compton scattering formula to the positions of the first and second interactions to deduce the angle of the incident gamma ray to within a certain cone-shaped area.

According to Vetter, the ultimate gamma-ray detector would be one that can precisely determine the path of an electron after a gamma ray initially impacts the detector. Such a system would require a resolution of better than 10 micrometers. He adds, "If we could measure the electron's path, we could determine the direction of the incident gamma ray unambiguously, rather than within the area of a cone."

The high-resolution silicon and germanium detectors must remain at low temperatures to operate, so UC's Space Sciences Laboratory built cryostats cooled by liquid nitrogen for the Compton imager. The second-generation instrument

^{22}Na source
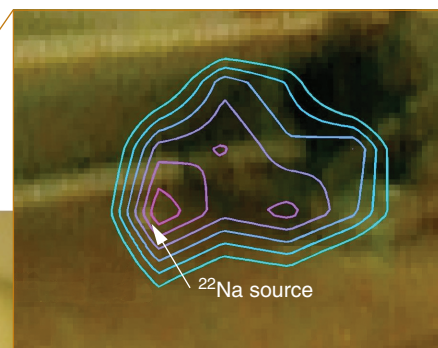
A Compton imager combined with a camera produced this image, which pinpoints the location of the radioactive source—an isotope of sodium (^{22}Na).

uses two cryostats—one for the two silicon detectors and one for the two germanium detectors. The third and final Compton imaging system, which the team plans to complete in 2008, will have one cryostat for all four detectors.

Future Design Possibilities

One drawback to using liquid nitrogen is that it requires frequent refills and large dewars, which complicate the instrument's operational capabilities. The team will explore the use of mechanical cooling for future systems. With mechanical cooling, the imagers could be used remotely for a wider range of applications. The Laboratory has developed portable radiation detectors, such as Cryofree/25 and RadScout (licensed by ORTEC under the name Detective®), which use germanium detectors that are mechanically cooled. The team will also research the possibility of using materials

such as silicon and cadmium–zinc–telluride so the detector could operate at room temperature. The overall effort will define a Compton imaging module that is best suited for homeland security. "Once we complete the design of the third-generation Compton imager," says Vetter, "scaling to larger systems would just be a matter of assembling multiple modules."

The team is using measurements taken with the first-generation system to calibrate such parameters as energy, depth, and position interpolation and is assembling the second-generation instrument. Livermore's imager is the most efficient and sensitive, fully operational Compton imaging system that has been built. The only other deployed system is the National Aeronautics and Space Administration's COMPTEL telescope. COMPTEL, built in 1989 to study gamma-ray sources such as pulsars and supernova remnants, uses

large-volume sodium iodide detectors, which provide limited sensitivity.

Ultimately, Livermore's Compton imager will provide a spatial resolution of about 3 by 3 square meters or less at a distance of 100 meters, with a 500-meter-diameter field of view. Weighing less than 460 kilograms, this portable system will allow security officials to conduct wide-area surveillance from the ground or in the air.

The goal for researchers designing radiation detection instruments is to maximize an instrument's sensitivity in detecting and identifying gamma rays from illicit sources in the midst of radiation from other sources. Livermore's large-area gamma-ray imager and its Compton imager add two powerful instruments to the DHS arsenal of equipment designed to help keep the nation safe.

—*Gabriele Rennie*
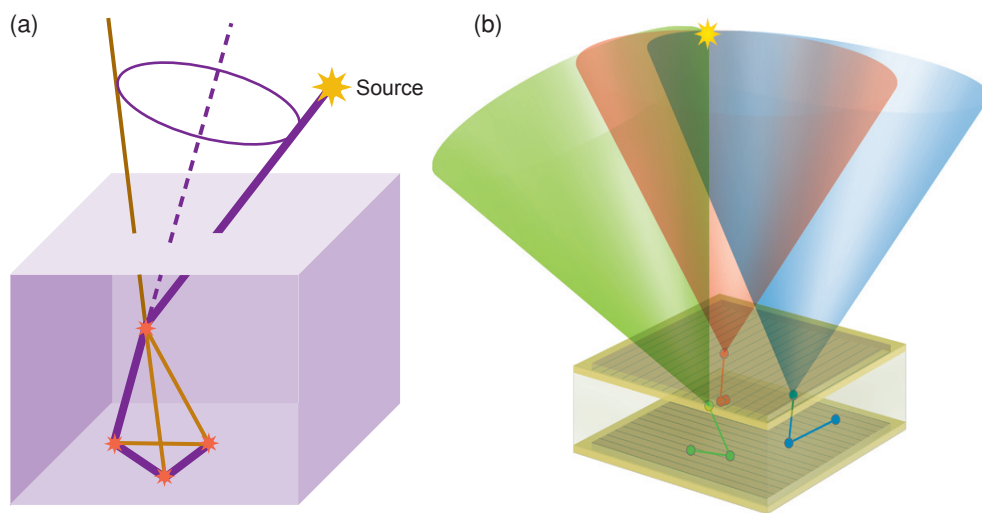
Incoming gamma rays interact with the detector through Compton scattering. (a) The energies and positions of the first two interactions define a cone of incident angles. (b) The cones can be projected onto a plane or sphere (one circle per gamma-ray event) to produce a two-dimensional image of the source.